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Deformations as a New Criterion for Dimensioning of Plastic Structures

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ABSTRACT

The strength and stability calculation of plastic structural components requires novel rules of dimensioning. A new model is introduced.

INTRODUCTION

During several years of research work a new, very simple method for the strength calculation of arbitrarily loaded plactic structural components was developed at the Institut für Kunststoffverarbeitung an der RWTH Aachen.

This method is based on the observation that, on the one hand, irreversible deformations are material-specific indications of damage and that, on the other hand, design-influenced failure such as buckling appears at the very moment the exactly definable coefficients of permissible deformation are exceeded.

The advantage of this new method is that only one characteristic diagram is needed for all kinds of stressing. This method allows for dimensioning—contrary to presently used methods—with great safety though only small safety factors are used.

These new, clear, and easy-to-handle rules of dimensioning are being applied in practise.

DEFORMATION AND DAMAGE BEHAVIOR SHOWN BY GLASSLIKE AMORPHOUS THERMOPLASTICS

Ductile materials show irreversible deformations as soon as their defined values of permissible strain are exceeded. These involve the exchange of places between the atomic and molecular components of a structure, and are generally called dislocations or flow zones [1]. The flow zones of amorphous thermoplastics (e.g., PMMA, PC, PVC) are orientation ranges caused by the stretching of molecular threads.

This leads to the refraction of light, and a silvery glimmer (crazes) can be seen on the surface of translucent thermoplastics. The formation of flow zones leads to plastic deformations, which are reversible above the glass transition temperature range of amorphous thermoplastics.

FORMATION OF FLOW ZONES (CRAZING) DURING UNIAXIAL TENSILE LOAD

It has been observed [1-3] that the deformation values which have been determined during the formation of flow zones tend over time to be asymptotic to a limiting value $\epsilon_{F\infty}$ (see Fig. 1) which differs insignificantly for thermoplastics with similar mechanical characteristics. The lower the initial stress ratio and the longer the induction period, the more distinct and of smaller number will be the flow zones.

The stress-strain behavior in the range below the deformation value curve ϵ_F shows linear and pseudoelastic characteristics, i.e., the deformation is retarded entirely within a relatively short period after unloading.

KIND OF STRESSING AND FORMATION OF FLOW ZONES (CRAZING)

The existing state of deformation (i.e., the maximum strain value) is decisive in the formation of flow zones. Multiaxial loading is of no influence on the flow deformation curve, as Fig. 2 shows. The limiting values for the moment of reaching flow deformation are identical under uni- and multiaxial tensile loads [2, 5].

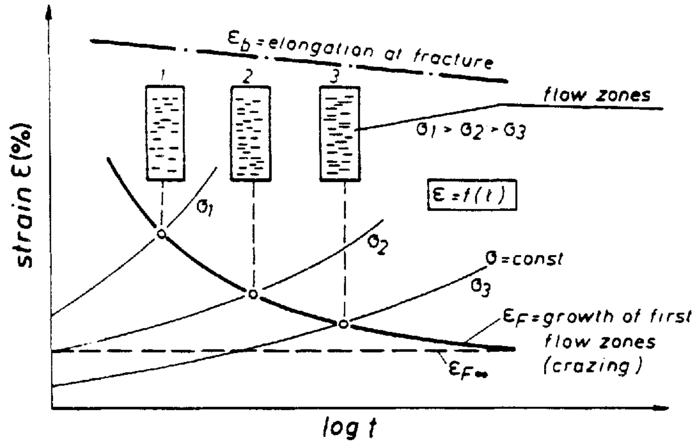

FIG. 1. Line of first onset of flow zones during the unidimensional creep test. There are schematic indications of the size and position of the flow zones formed.

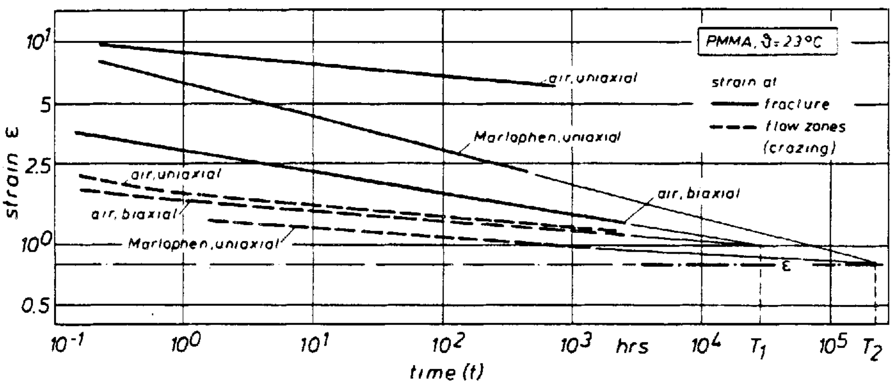

FIG. 2. Curves of elongation at break (——) and at crazing (- -) under uniaxial and biaxial static stress in air and in a wetting agent for PMMA pipes at 23°C, indicating the effect of environment on the slope of the elongation curve.

Retardation experiments with cyclic loading and unloading periods show that viscoelasticity as a superposition of reversible and irreversible deformation is of little consideration on the behavior of amorphous thermoplastics [1]. The deformations are reversible as long as the flow zones initiating strain values, which also lead to flow zones during the creep test with static uniaxial tensile load, are not exceeded. The limiting values of flow deformation ϵ_F — known as $\epsilon_{F\infty}$ during longer loading periods—are to be interpreted as time elasticity limits for amorphous thermoplastics. Cyclic loading and unloading of a material does not lead to increased stressing.

The limiting deformation value $\epsilon_{F\infty}$ is preserved even during pulsating tensile load. On the contrary, the flow deformation curve $\epsilon_F = f(t)$ (see Fig. 4) moves, in accord with the results of static long-term tests under increased temperatures, because of increasing self-heating to shorter induction periods during growing vibrational amplitude.

As Ref. 4 showed, the influence of diverse kinds of stressing and environmental effects on the formation of flow zones and on the fracture behavior may be schematically represented by Fig. 3. The formation of flow zones in the range of very short loading periods (high deformation velocity) is only possible as long as certain minimum induction periods for the formation of flow zones exist. The decrease of rupture strain is only possible to a minimum limit as described by $\epsilon_{F\infty}$ [2].

EFFECT OF ENVIRONMENTAL MEDIUMS ON THE FORMATION OF FLOW ZONES

The application of subaerially measured flow deformation values in the presence of surface-active mediums is possible as long as these mediums do not initiate a change of condition of the basic material [2]. There are similar atmospheric characteristics for the limiting deformation value $\epsilon_{F\infty}$; although the flow zone initiating deformation may be reduced, the limiting value $\epsilon_{F\infty}$ remains unchanged (Fig. 2).

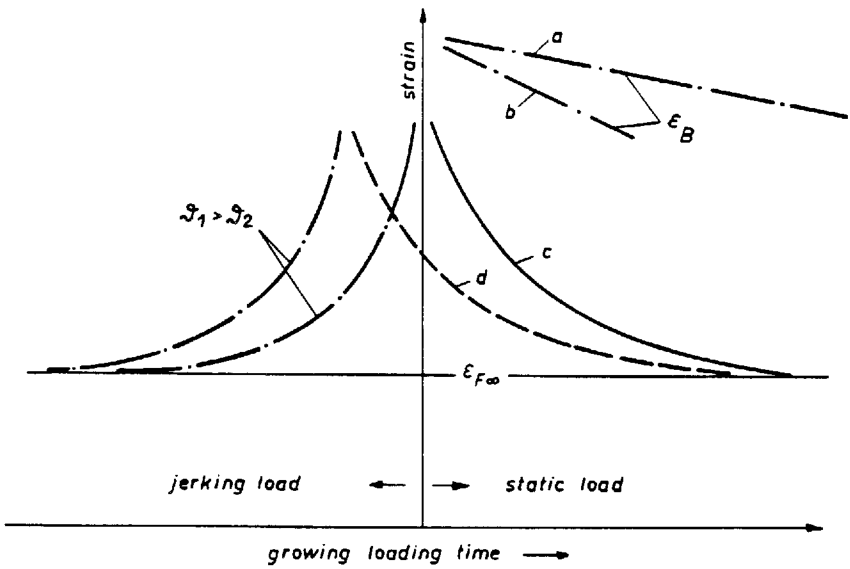

FIG. 3. Flow deformation ϵ_F, limiting flow deformation $\epsilon_{F\infty}$, and elongation at fracture ϵ_B as well as functions of time and environmental effects as different kinds of time-dependent stressing. θ: Temperature. a: Elongation of fracture under tensile load (ϵ_B). b: ϵ_B = f (time, multiaxial load). c: ϵ_F at room temperature. d: ϵ_F at high temperatures in environmental mediums which lead to no change of condition of the basic material at pulsating load.

FORMATION OF FLOW ZONES UNDER INCREASED ENVIRONMENTAL TEMPERATURES

The limiting deformation value $\epsilon_{F\infty}$ is independent of the environmental temperature (Fig. 4) as well, as long as no change of the material condition (e.g., the glass transition temperature) takes place [2, 3].

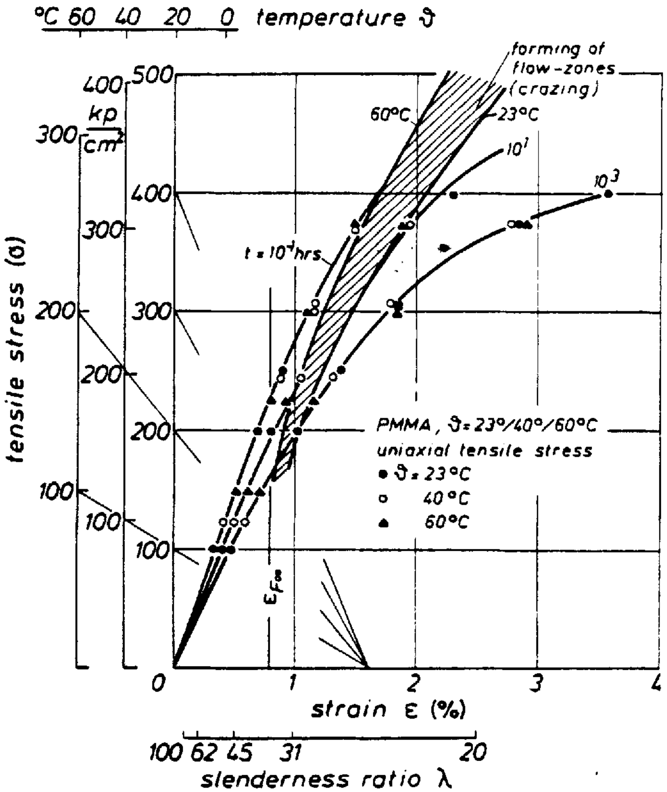

FIG. 4. Isochronous stress-strain diagram for various temperatures, times, and slenderness ratios.

Elongations during the formation of flow zones will be reached after shorter periods under increased temperature. The closer the ratio of the test temperature and glass transition temperature is to 1, the sooner the flow deformation curve ϵ_F will tend to the—always constant—limiting deformation value $\epsilon_{F\infty}$. This means that increased temperatures lead to a fast motion effect of the state of material under low temperatures.

PRACTICAL CONCLUSIONS

For the practical design of plastic constructions it is rather important that the limiting deformation value $\epsilon_{F\infty}$ is neither affected by the kind of stressing (static, cyclic, pulsating, jerking) nor by the stress distribution (uni- or multiaxial), nor by the time, the environmental temperatures, and the kind of medium described. Therefore the limiting flow deformation value, as a constant material characteristic, is an ideal basis for dimensioning.

Partially crystalline thermoplastics show similar phenomena. Crazes—analogous the flow zones of amorphous thermoplastics—will be seen on the limiting surface of spherolites of partially crystalline thermoplastics. Based on our previous experiments, glass fiber reinforced plastics (GRP) show similar relations in crazes which originate from the boundary surface of the glass fiber/resin as soon as a critical deformation value is reached.

DIMENSIONAL RULES. DEFORMATION BEHAVIOR UNDER MULTIAXIAL MECHANICAL LOAD

In case the ratio of the existing principal stresses of a structural part of known geometry is available, it is possible to find the effectively existing principal deformation values of a multiaxial loaded structural part ($\epsilon_{1...3}$)—as described by the expanded Hookean law—by the use of an isochronal stress/strain diagram and by means of a linear superposition of strain values achieved during uniaxial load $\epsilon_{\sigma_{1...3}}$:

$$\epsilon_{1,2,3} = \epsilon_{\sigma_{1,2,3}} - \mu(\epsilon_{\sigma_{2,3,1}} + \epsilon_{\sigma_{3,1,2}}) \tag{1}$$

For glasslike amorphous thermoplastics as well as for GRP the transverse contraction ratios are practically time-independent [2, 6]. For anistropic reinforced plastics the directional dependence of the transverse contraction ratio has to be considered.

STABILITY CALCULATION OF PLASTIC STRUCTURES

The question of stability of construction elements made of plastics is of more decisive importance than it is for other constructional materials since the moduli of elasticity are relatively low in comparison to the strength values. This leads to the fact that increased attention has be paid to a calculation of stability, which is contrary to the calculation methods of common materials for which the compressive strength is often critical.

Since the moduli of elasticity are dependent on time and sometimes on the magnitude of the effective stress, a stability calculation by common means is rather complicated.

The problem is to evaluate the knowledge gained by dimensioning and testing different stability conditions of other materials by means of a rather exact and practicable method.

Based on stability experiments with different construction elements (slender bars, cylindrical shells under radial and axial pressure, disks undergoing shear stress) made of various plastics and on theoretical considerations [7, 8], we can prove that unstable failure always starts at the very moment a condition of critical deformation—which is determined only by the slenderness ratio λ, i.e., the geometry and the clamping conditions of the loaded structural part—is exceeded.

It is possible to describe these relations with the "theory of critical compressive strain" which is derived, for slender bars, from the Euler equation:

$$\epsilon_K = \sigma_K/E = \pi^2/\lambda^2 \tag{2}$$

where λ = slenderness ratio, E = modulus of elasticity, K = critical index, ϵ = compressive strain, and σ = stress. This equation remains valid in the elastic "Euler range," and in the elastic-plastic "Tetmajer range."

Therefore, on the one hand the critical compressive strain values are loading-time independent deformation limits; i.e., for creeping materials it is possible to transfer critical deformation values measured during short-time tests to long-term experiments. On the other hand, those limiting values of acceptable structural component deformation are material-independent characteristics which allow the transfer of known (experimentally proved) critical compressive strain rates of common materials to similar stability problems of new materials. Based on this fact, the technical application of newly developed materials for loaded components may become enormously accelerated.

The introduction of a equivalent slenderness ratio, λ_V, allows the transfer of the "theory of critical compressive strain"—as the criterion of unstable failure by buckling —to spherically curved and disk-shaped structural component geometries. The classical laws of buckling are easily transformable by means of

$$\lambda_v = \pi(E/\sigma_k)^{1/2} \tag{3}$$

The experimentally found critical compressive strain values—as criteria of unstable failure by buckling—lie, when plotted against the slenderness ratios λ and λ_v, as Fig. 5 shows, directly below the theoretical function.

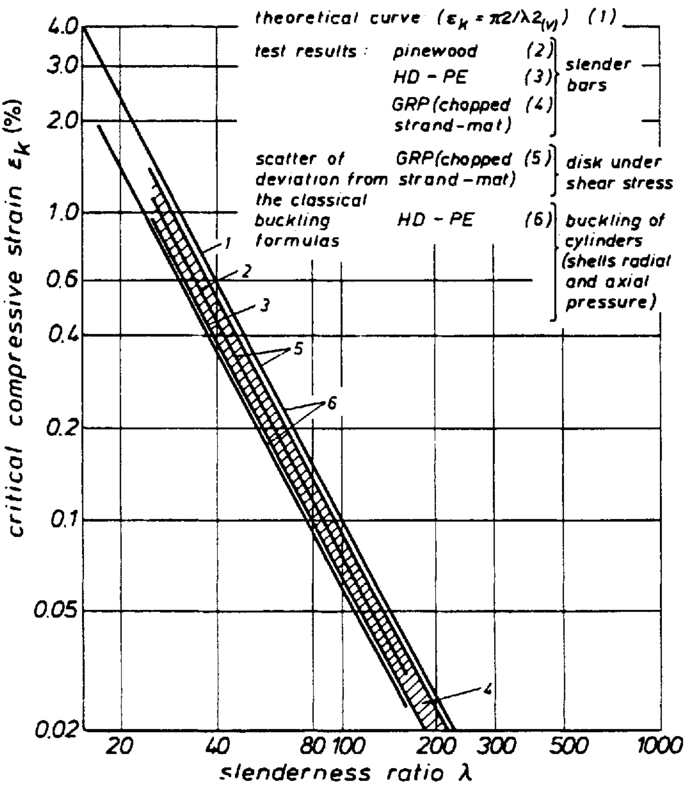

FIG. 5. Critical compressive strain as a function of the slenderness ratio for several construction elements.

Similar and sometimes major differences from the theoretical values of the classical buckling stress relations are known for common materials, e.g., steel.

In general a single diagram, as shown in Fig. 4, is sufficient for practical calculations. The isochronous stress-strain curves allow a direct assignment of load and deformation for all temperatures and loading periods.

In addition, for stability problems the slenderness ratios, as shown in Eq. (2), are directly assignable to the specific critical deformation values.

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